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# Modelling Laser Matter Interaction with Tightly Focused Laser Pulses in Electromagnetic Codes

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**Abstract:** We propose an algorithm to introduce arbitrarily shaped laser pulses into electromagnetic codes. In contrast to the often used paraxial approximation our approach models accurately tightly focused laser pulses and their interaction with matter.

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Investigation of laser matter interaction with electromagnetic codes requires to implement sources for the electromagnetic fields. A common practise to do so is to prescribe the fields at the numerical box boundaries in order to achieve the desired fields inside the numerical box. Very often, the paraxial approximation is used to calculate the required fields at the boundaries. However, the paraxial approximation is valid only if the angular spectrum of the laser pulse is sufficiently narrow. Thus, it is not possible to use this approximation for strongly focused pulses. We propose a simple and efficient algorithm for a Maxwell consistent calculation of the electromagnetic fields at the boundaries of the computational domain. We call them laser boundary conditions (LBCs).

In numerical studies of laser matter interaction, one usually defines the laser by its propagation in vacuum, for example, by position and shape of the pulse at focus. In this paper, we choose to prescribe the pulse in a plane  $\mathbb{P}$  parallel to a boundary of the rectangular numerical box, i.e., typically in the focal plane [see Fig. 1 (a)]. The laser (red) is passing through the plane  $\mathbb{P}$ , where the fields  $\mathbf{E}_0$ ,  $\mathbf{B}_0$  are prescribed for all times  $t$ . The goal is to calculate the fields  $\mathbf{E}_B$ ,  $\mathbf{B}_B$  at the boundary from  $\mathbf{E}_0$ ,  $\mathbf{B}_0$ .

The fields  $\mathbf{E}_0$ ,  $\mathbf{B}_0$  describe forward and/or backward propagation waves indicated by the superscript  $\pm$  in the following. It is important to note that  $\mathbf{E}_0^\pm$ ,  $\mathbf{B}_0^\pm$  cannot be chosen arbitrarily. In fact, only two out of six vector components (for forward and backward direction, respectively) are independent. For example, we can choose to prescribe  $\mathbf{E}_{0,\perp}^\pm$  in the plane  $\mathbb{P}$ . Then, by exploiting the Maxwell's equations in vacuum, we get all the other fields in frequency  $\omega$  and transversal Fourier space  $(k_x, k_y)$  along the propagation direction  $z$  as

$$\bar{\mathbf{E}}_\perp^\pm(\mathbf{k}_\perp, z, \omega) = \bar{\mathbf{E}}_{0,\perp}^\pm(\mathbf{k}_\perp, \omega) e^{\pm i k_z(\mathbf{k}_\perp, \omega)(z-z_0)} \quad (1)$$

$$\bar{E}_z^\pm(\mathbf{k}_\perp, z, \omega) = \mp \frac{\mathbf{k}_\perp \cdot \bar{\mathbf{E}}_\perp^\pm(\mathbf{k}_\perp, z, \omega)}{k_z(\mathbf{k}_\perp, \omega)} \quad (2)$$

$$\bar{\mathbf{B}}^\pm(\mathbf{k}_\perp, z, \omega) = \frac{1}{\omega k_z(\mathbf{k}_\perp, \omega)} \mathbb{R}^\pm(\mathbf{k}_\perp, \omega) \bar{\mathbf{E}}_\perp^\pm(\mathbf{k}_\perp, z, \omega), \quad (3)$$

with the matrix  $\mathbb{R}^\pm$  and  $k_z$  according to

$$\mathbb{R}^\pm(\mathbf{k}_\perp, \omega) = \begin{pmatrix} \mp k_x k_y & \mp [k_z^2(\mathbf{k}_\perp, \omega) + k_y^2] \\ \pm [k_z^2(\mathbf{k}_\perp, \omega) + k_x^2] & \pm k_x k_y \\ -k_y k_z(\mathbf{k}_\perp, \omega) & k_x k_z(\mathbf{k}_\perp, \omega) \end{pmatrix} \quad (4)$$

$$k_z(\mathbf{k}_\perp, \omega) = \sqrt{\omega^2/c^2 - k_x^2 - k_y^2}. \quad (5)$$

Thus, transforming the given fields  $\mathbf{E}_0$ ,  $\mathbf{B}_0$  into the frequency and transversal Fourier space, evaluating Eqs. (1)-(3) and performing the Fourier back transforms gives the required fields at the boundary. Adding them to the boundary adapted to the grid of the specific Maxwell solver introduces the desired fields in the numerical box.

To demonstrate the significance of Maxwell consistent LBCs, the distributions of the electron density  $n_e$  after a tightly focused Gaussian pulse has passed an initially neutral gas is considered. We perform the computations with the PIC code OCEAN [1] using paraxial approximation and the Maxwell consistent approach. For both cases a linear

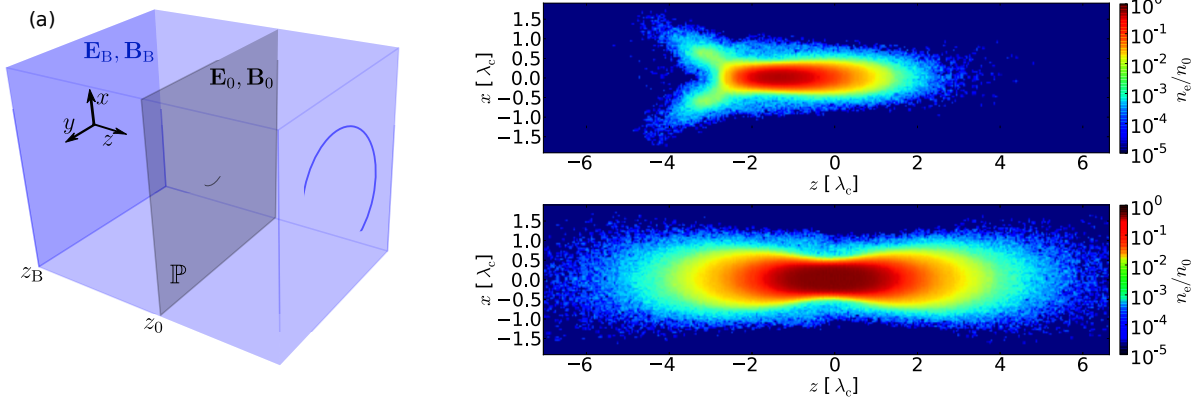


Fig. 1. Schematic picture (a) of the laser (red) injection problem into the computational domain: Electric and magnetic fields  $\mathbf{E}_0, \mathbf{B}_0$  are prescribed in the plane  $\mathbb{P}$  [here the  $(x, y)$ -plane at  $z = z_0$ ]. The fields  $\mathbf{E}_B, \mathbf{B}_B$  at the boundary (blue) are unknown and have to be calculated. Electron densities  $n_e$  produced by tightly focused Gaussian laser pulses: The profile produced by paraxial LBCs (a) is even qualitatively different than the one produced by Maxwell consistent LBCs (b). Electron densities are scaled to the initial neutral density  $n_0$ . The laser propagates from left to right.

polarized two dimensional ( $\partial_y = 0$ ) Gaussian pulse is prescribed in the focal plane  $z = z_0$  by

$$\mathbf{E}_{0,\perp}(x, t) = E_0 e^{-\left(\frac{x}{w_0}\right)^2 - \left(\frac{t}{t_0}\right)^2} \cos(\omega_c t) \mathbf{e}_x, \quad (6)$$

with center wavelength  $2\pi c/\omega_c = \lambda_c = 0.8 \mu\text{m}$ , pulse duration  $t_0 = 20 \text{ fs}$ , peak intensity  $I_0 = \epsilon_0 c |E_0|^2 / 2 = 5 \times 10^{14} \text{ W/cm}^2$  giving  $E_0 = 61.4 \text{ GV/m}$  and beam width  $w_0 = 0.35 \mu\text{m}$ . The particular choice of the beam width  $w_0$  implies that non-negligible parts of  $\tilde{\mathbf{E}}_{0,\perp}(k_x, \omega)$  are evanescent. These evanescent fields are suppressed in the calculation of  $\mathbf{E}_B(\mathbf{r}_\perp, t)$  and  $\mathbf{B}_B(\mathbf{r}_\perp, t)$  at the boundary  $z = z_B$ , fully compatible with Abbe's diffraction limit.

The resulting distributions of the electron density  $n_e$  after the laser pulse has passed through the interaction region are shown in Fig. 1 (b - c). The electron density profiles are even qualitatively different for paraxial and Maxwell consistent LBCs: The paraxial LBCs give a fish-like shape, where before the focus (negative  $z$ ) the peak electron density appears off-axis [see Fig. 1(a)], and only up to 60% of the argon atoms get ionized. In contrast, the Maxwell consistent LBCs produce a cigar like shape with the peak electron density on the optical axis [see Fig. 1(b)], and a fully ionized plasma is produced. We would like to stress that these deviations in the plasma profile are far from negligible, and may have significant impact on features like back-reflected radiation or energy deposition in the medium. The observed sensitivity towards the LBC for tight focusing is not limited to ultrashort low energy pulses interacting with gaseous media, but should be equally important for solid targets and higher pulse energies.

Beside an accurate handling of the tightly focused Gaussian laser pulse injection, our algorithm offers a simple way to simulate more complex pulse configurations or even sampled experimental beam profiles [2]. Such "structured light" receives a lot of recent interest from various communities [3]. Thus, we believe that our approach will be useful for a larger community working on electromagnetic simulation codes.

## References

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